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14. ABSTRACT

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15. SUBJECT TERMS

Sediment property data, Siliciclastic sediment, Calcareous sediment

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RELATIONSHIPS AMONG SEDIMENT PHYSICAL AND ACOUSTIC PROPERTIES IN SILICICLASTIC AND CALCAREOUS SEDIMENTS

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Since the early 1980s, the authors have collected nearly 800 cores at 69 shallow-water sites around the world (12 calcareous and 57 siliciclastic sites). Siliciclastic sites ranged from soft mud through coarse sand and calcareous sites consisted of molluskan shells, shell hash, carbonate reef debris, and calcareous particles formed by chemical precipitation. The cores were carefully collected by divers from shallow water or sub-sampled from box core samples retrieved from deeper waters. For most sediment samples compressional wave speed and attenuation (at 400 kHz) were measured at 1-cm intervals and sediment physical properties (porosity, bulk density, grain density, and grain size distribution) were determined from 2-cm-thick sections from the same core. Data are typically restricted to the upper 30 cm of sediment. Based on the nearly 4500 common data points resulting from core measurement (3922 siliciclastic and 621 calcareous) regressions were determined among sediment physical and acoustic properties.

1. INTRODUCTION

Compilations of sediment property data have been widely used for constructing geoacoustic models [1-5] and interpreting remotely obtained acoustic measurements of surficial sediments [6, 7]. From experience, the most widely available sediment property that can be used to predict values of acoustic and other physical properties is sediment type. More specifically, the mean grain size (M_z) value is used as a salient characteristic for making predictions of sediment properties. However, particle-particle interactions and natural variability within grain size distributions complicate the relationship between the sediment grain size and acoustic and physical properties. Physical behavior and interactions among sand- and silt-sized grains differ significantly from those of clay-sized particles. Sediments are rarely homogeneous distributions (unimodal and leptokurtic) of particles, but are often mixtures of a variety of sediment grain sizes and particle types. Furthermore, the shape of particles (i.e., angularity, roundness, platy-ness) will affect sediment properties due to the interaction among the particles at the grain contacts.

There are many different types of sediment distributions among the 69 sites on which we report, yet there are significant omissions in terms of heterogeneous sediments. Most sites were chosen because of the relative uniformity of the sediments. Nevertheless, a broad spectrum of mean grain sizes are presented from coarse shell hash to clay, and from two types of sediments: siliciclastic and calcareous. These two sediment types are considered different enough in terms of their source (geological *vs.* biological), predominate mineralogy (Si *vs.* Ca), and grain structure (solid *vs.* porous) that they are often segregated when devising empirical relationships [8].

The grain size spectrum over which the variation of properties of sediment compressional wave velocity, compressional wave attenuation, porosity, bulk density, percent gravel, sand, silt, clay, and grain sorting is displayed allows insights into acoustic propagation and scattering in sediments. Empirical relationships are presented as curvilinear regressions and evaluated in terms of the coefficient of determination (r^2), which signifies the proportion of the variation of one sediment property determined by the variation of the other sediment property.

2. METHODS

Sediment geoacoustic and physical property measurements were made from sediments collected with 45-cm-long, 5.9-cm-inside-diameter, clear, polycarbonate coring tubes. Most sediments were collected by divers but sediments collected from eight sites (Montauk Point, Quinault Range, Arafura Sea, Russian River, Eel River, North Sea , TOSSEX, and Straits of Juan de Fuca), which were too deep for diving operations, were subsampled from 0.25m^2 spade box cores. Cores were capped at both ends immediately after collection to retain the overlying water and kept in an upright position during transport to the laboratory for analysis. Collection, measurement, and handing procedures were designed to minimize sampling disturbance and to maintain an intact sediment-water interface within the coring tube.

Sound speed and attenuation were measured on sediment at 1-cm intervals within the core tubes, usually within 24 hours of collection, using time-of-flight and amplitude of pulsed 400-kHz sine waves transmitted across the core tube [3]. Sediment sound speed is calculated from the differences in time-of-flight between sediment and distilled water within identical core tubes, the measured inside diameter of the core tube (5.9 cm), and the sound speed within the distilled water. Attenuation is measured as 20 log of the ratio of the mean amplitude of the waveform transmitted through water to that transmitted through sediment. Sound speed is reported as the unitless sound speed ratio (V_p *ratio*) which is the ratio of measured sound speed to the sound speed of pore water at the same temperature, salinity and pressure. Attenuation is expressed in units of dB m^{-1}kHz^{-1} (k) after Hamilton [2].

Sediments were then extruded from sediment cores and sectioned at 2-cm intervals to determine sediment porosity and grain size distribution. Porosity was determined from weight loss of sediments dried at 105° C for 24 hours and corrected for residual salt. Grain density was determined using a pyncnometer. Sediment bulk density was calculated from the porosity and densities of pore water and sediment grains. Sediment grain size was determined from disaggregated samples by dry sieving for sand-sized particles and by either pipette methods or Micromeritics sedigraph for silt- and clay-sized particles. Grain diameter is expressed in phi (ϕ) units.

Sediment impedance is the product of sediment sound speed and bulk density. Sediment sound speed is dependent on pore water temperature and salinity and pressure (water depth) and values can vary up to 10% over the range of seasonal conditions expected in coastal

waters [6]. Therefore, the pore-water-independent Index of Impedance (IOI), which is the product of the sediment bulk density and velocity ratio, is used to calculate empirical relationships between sediment impedance and other sediment physical properties [6,7].

3. RESULTS AND DISCUSSION

We collated the parameters of sediment sound speed (V_p, m s^{-1}), sediment sound speed ratio (V_pR, unitless), attenuation (α, dB m^{-1}; k, dB m^{-1}kHz^{-1}), mean grain size (M_z, ϕ), sediment porosity (η, %), sediment bulk density (ρ, g cm^{-3}), Index of Impedance (IOI, g cm^{-3}) and sediment type for the 57 siliciclastic sites in Table 1 and the 12 calcareous sites in Table 2. The siliciclastic and calcareous sites are arranged in order of increasing mean grain size (decreasing values of ϕ), from clay to coarse sand or shell hash. Sound speed ratio is highly correlated with both bulk density and porosity, and to a lesser degree mean grain size (Fig. 1).

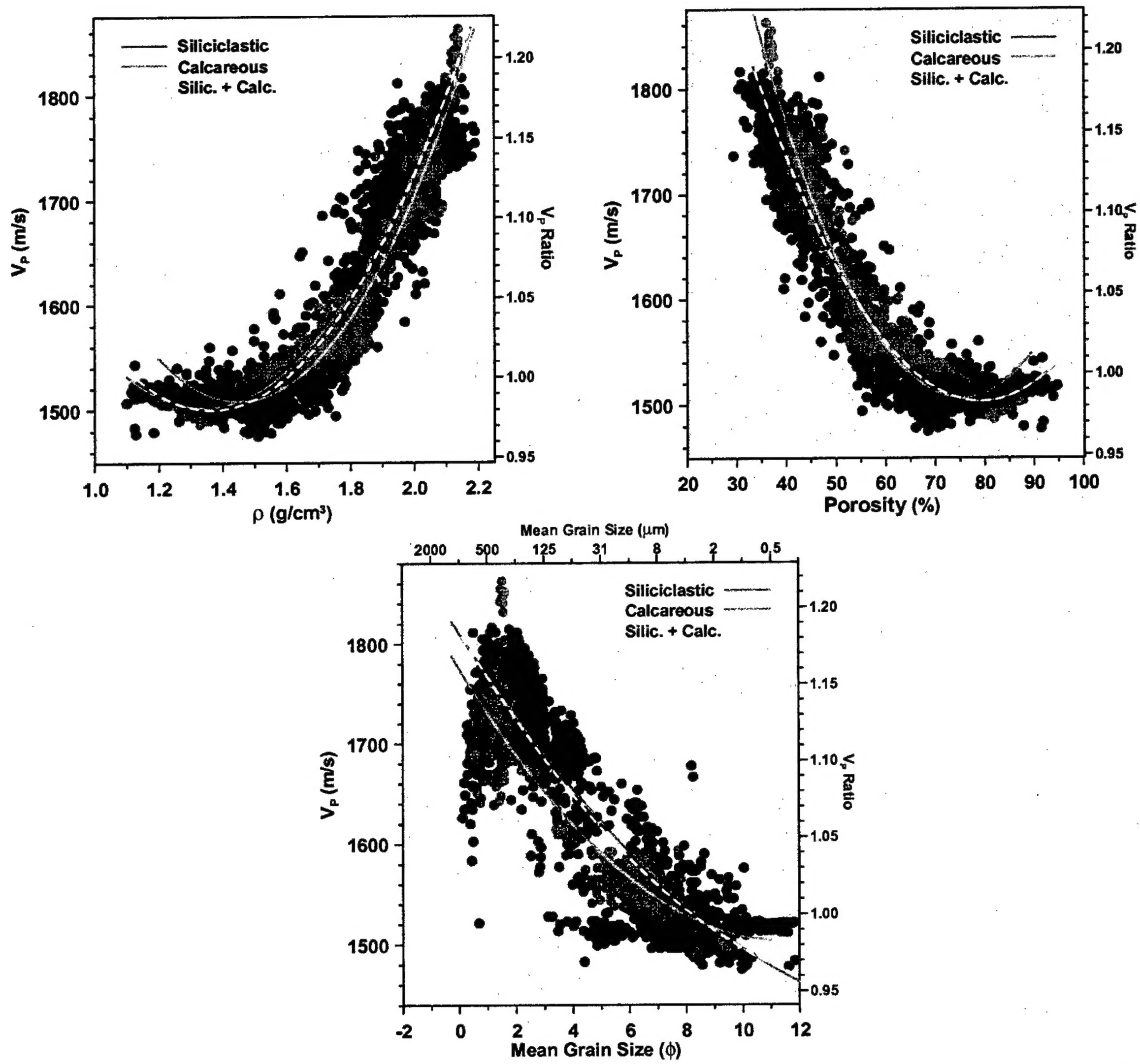

Fig 1. Sound speed and velocity ratio as a function of bulk density (ρ), porosity, and mean grain size. The lighter symbols, which represent calcareous sediments, overlay the darker symbols which represent siliciclastic sediment. Equations for regressions are given in Table 3.

Site	V_p	*VpR*	α	M_z	η	ρ	k	*IOI*	Sediment
SABay	1518.9	0.993	38.7	10.94	89.14	1.170	0.097	1.162	clay
Diga	1480.4	0.968	58.0	10.05	69.12	1.506	0.145	1.458	silty clay
Eck93	1515.5	0.991	72.3	9.88	87.40	1.188	0.181	1.177	silty clay
Portovenere	1501.7	0.982	66.2	9.45	68.30	1.546	0.166	1.518	silty clay
Viareggio	1511.3	0.988	99.5	8.98	61.74	1.634	0.249	1.615	silty clay
STeresa	1502.4	0.982	122.3	8.78	66.98	1.569	0.306	1.541	silty clay
JDF7	1507.2	0.985	114.2	8.50	83.43	1.313	0.285	1.294	silty clay
CLBight	1521.9	0.995	114.0	8.10	86.50	1.223	0.285	1.216	silty clay
Orcas	1511.9	0.988	179.1	8.08	75.22	1.403	0.448	1.387	clayey sand
LISound	1503.1	0.982	—	7.64	76.64	1.411	—	1.386	clayey silt
EelRiver	1554.6	1.016	190.7	7.17	57.32	1.745	0.477	1.773	clayey silt
JDF4	1521.7	0.995	206.8	6.93	74.35	1.470	0.517	1.462	glacial till
RussRiver	1545.5	1.010	231.8	6.35	64.35	1.597	0.579	1.613	clayey sand
Tellaro	1614.4	1.055	184.7	6.08	50.70	1.820	0.462	1.921	sand-silt-clay
Arafura	1511.4	0.988	347.8	5.24	71.63	1.494	0.869	1.476	clayey sand
Monasteroli	1652.4	1.080	220.2	5.12	46.62	1.891	0.550	2.042	sand-silt-clay
Eck94	1609.7	1.052	210.7	4.59	59.38	1.659	0.527	1.745	sand-silt-clay
JDF1	1617.6	1.057	238.5	4.37	55.37	1.800	0.596	1.903	silty fine sand
VAzzura	1686.4	1.102	156.5	4.14	45.17	1.911	0.391	2.106	muddy sand
Misby/fine	1682.4	1.100	195.8	3.77	—	—	0.489	—	v.fine sand
Tirrenia	1683.1	1.100	127.6	3.72	45.76	1.906	0.319	2.097	v.fine sand
JDF6	1668.2	1.090	314.3	2.94	47.56	1.922	0.786	2.096	fine sand/s-s-c
Quinault	1709.3	1.117	177.2	2.94	41.76	1.971	0.443	2.202	fine sand
TBay/fine	1746.0	1.141	206.1	2.92	40.16	2.013	0.515	2.297	fine sand
PC84	1742.9	1.139	241.7	2.61	40.08	1.998	0.604	2.276	fine sand
ATB/G40	1651.9	1.080	219.8	2.56	56.61	1.716	0.549	1.853	fine sand
LTB	1716.8	1.122	317.1	2.54	43.57	1.929	0.793	2.165	fine sand
Duck	1758.8	1.150	116.2	2.53	39.54	2.051	0.291	2.357	fine sand
MVCO	1755.1	1.147	154.5	2.52	38.49	2.028	0.386	2.327	fine sand
PCB I&II	1755.1	1.147	176.1	2.34	39.72	2.018	0.440	2.315	fine sand
JDF5	1701.5	1.112	213.8	2.31	45.44	1.946	0.534	2.164	fine sand/s-s-c
PCB99	1764.2	1.153	133.5	2.24	39.33	2.020	0.334	2.329	fine sand
SWEAT	1747.6	1.142	213.3	2.23	40.38	2.007	0.533	2.292	fine sand
ATB/B14	1752.6	1.146	107.2	2.15	39.52	2.006	0.268	2.298	fine sand
SG98-8	1747.1	1.142	265.7	2.14	39.65	2.026	0.664	2.314	shelly fine sand
MonPt	1744.4	1.140	92.1	2.04	37.21	2.045	0.230	2.332	fine sand
JDF2	1771.6	1.158	179.5	2.03	39.10	2.039	0.449	2.361	medium sand
Charl/fine	1728.4	1.130	281.0	1.97	39.94	2.001	0.703	2.260	fine sand
NoSea	1779.0	1.163	155.7	1.93	37.56	2.054	0.390	2.388	med/fine sand
TOSSEX	1762.7	1.152	161.8	1.93	35.64	2.075	0.404	2.391	med/fine sand
NS	1735.0	1.134	226.1	1.87	41.07	2.046	0.565	2.320	medium sand
IRB	1745.2	1.141	281.2	1.77	40.63	2.023	0.703	2.307	medium sand
SG98-10	1752.1	1.145	164.1	1.62	40.69	1.979	0.410	2.266	medium sand
SG98-9	1747.1	1.142	206.7	1.56	39.45	2.010	0.517	2.295	medium sand
Charl/crse	1729.1	1.130	308.1	1.44	39.63	2.006	0.770	2.267	medium sand
TBay/crse	1754.2	1.147	610.2	1.36	44.85	1.966	1.526	2.254	coarse/fine sand
HoodCanal	1767.1	1.155	184.6	1.34	36.46	2.108	0.462	2.435	medium sand
KB/bar	1758.2	1.149	254.4	1.33	37.28	2.047	0.636	2.352	medium sand
PE99	1770.7	1.157	153.0	1.28	37.08	2.052	0.383	2.375	medium sand
SAX99	1766.3	1.154	177.5	1.27	37.27	2.066	0.444	2.385	medium sand
PE00	1774.1	1.160	149.5	1.21	37.32	2.050	0.374	2.377	medium sand
PC93	1708.5	1.117	404.0	0.98	40.93	2.008	1.010	2.242	coarse sand
Misby/crse	1762.4	1.152	145.4	0.95	—	—	0.357	—	coarse sand
KB/lyn	1709.2	1.117	586.9	0.90	40.14	2.020	1.467	2.256	shell hash
PCII	1716.4	1.122	391.2	0.85	41.09	2.000	0.978	2.244	c. sand/sh. hash
SG98-1	1713.0	1.120	430.2	0.84	40.66	2.053	1.076	2.299	shell hash
SG98-6	1649.6	1.078	632.5	0.08	43.47	2.001	1.581	2.158	shell/coral hash

Table 2. Summary of sediment physical and geoacoustic properties from 57 siliciclastic sites. Geoacoustic and physical properties consist of sound speed (V_p, $m\ s^{-1}$), velocity ratio (V_pR, no units), attenuation (α, $dB\ m^{-1}$ @ 400 kHz), mean grain size (M_z, phi), porosity (η, %), bulk density (ρ, $g\ cm^{-3}$), attenuation (k, $dB\ m^{-1}\ kHz^{-1}$), index of impedance (IOI, $g\ cm^{-3}$) and sediment type.

Regressions for siliciclastic and calcareous sediments are not significantly different and the authors suggest using the regression for the sediment types combined (Table 3). Attenuation is very poorly correlated with sound speed or density (Fig. 2; Table 3).

Attenuation as measured by our techniques, however, includes both intrinsic attenuation and the effects of scattering from both grains (such as shells) and larger scale heterogeneities. The lower bounds of attenuation may come close to representing intrinsic attenuation and, as such, closely mimic the attenuation values in scatter plots summarized by Hamilton [1], with the lowest values of attenuation in coarse-to-medium sand and clay and higher attenuation in the fine-sand to silt-sized range. Based on the data presented here, empirical relationships among attenuation and sediment physical properties have little predictive value at this high measurement frequency (400 kHz). The fact that regressions among sediment physical and acoustic properties are similar for calcareous and siliciclastic sediments and differ very little from regressions based on a much smaller data set presented by Richardson and Briggs [6] suggest a universal applicability of the regressions presented here.

Table 2. Summary of sediment physical and geoacoustic properties from 12 calcareous sites. Geoacoustic and physical properties consist of sound speed (V_p, m s^{-1}), velocity ratio (V_pR, no units), attenuation (α, dB m^{-1} @ 400 kHz), mean grain size (M_z, phi), porosity (η, %), bulk density (ρ, g cm^{-3}), attenuation (k, dB m^{-1} kHz^{-1}), index of impedance (IOI, g cm^{-3}) and sediment type.

Site	*Vp*	*VpR*	α	M_z	η	ρ	*k*	*IOI*	Sediment
Hawaii/mud	1495.3	0.977	68.6	8.67	84.02	1.296	0.171	1.267	calc. silty clay
DTortugas	1561.8	1.021	343.0	6.62	59.00	1.755	0.858	1.792	calc. s-s-clay
MarqKeys	1555.6	1.017	391.3	6.15	59.66	1.726	0.978	1.755	calc. s-s-clay
SG98-5	1560.8	1.020	322.3	5.85	59.59	1.748	0.806	1.783	calc. s-s-clay
LFK/fine	1581.3	1.034	365.8	5.40	57.19	1.759	0.914	1.818	calc. s-s-clay
Hawaii-4	1609.7	1.052	246.2	3.88	56.42	1.771	0.615	1.864	calc. silty sand
Hawaii-2	1671.6	1.093	438.3	2.33	47.68	1.933	1.096	2.112	calc. med. sand
SG98-3	1777.3	1.162	236.7	1.66	40.92	2.067	0.592	2.401	ooid/skel. sand
SG98-2	1669.4	1.091	383.1	1.57	49.47	1.921	0.958	2.096	crse. skel. sand
RebShoal	1733.1	1.133	279.1	1.26	43.85	2.022	0.698	2.290	carbonate sand
Hawaii/crse	1639.4	1.072	695.2	0.74	45.18	1.960	1.738	2.100	crse. coral sand
LFK/crse	1704.7	1.114	488.9	0.54	41.97	2.054	1.222	2.289	crse. coral sand

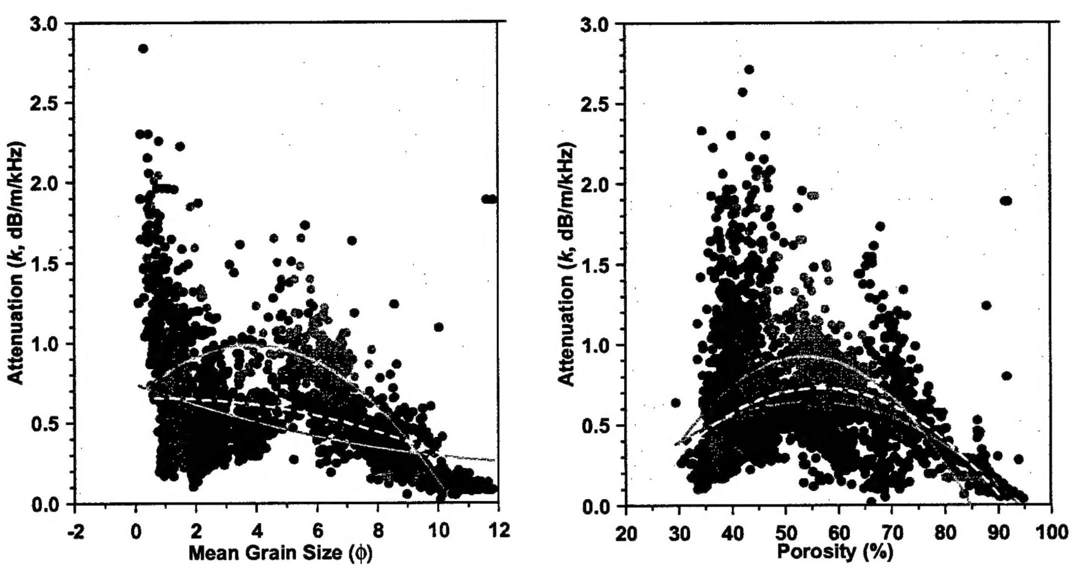

Fig 2. Attenuation, measured at 400 kHz, verses porosity, and mean grain size. The lighter symbols, which represent calcareous sediments, overlay the darker symbols which represent siliciclastic sediment. Equations for regressions are given in Table 3.

Table 3. Empirical relationships among sediment physical and geoacoustic properties for siliciclastic and calcareous sites. Geoacoustic and physical properties, velocity ratio (V_pR, no units), mean grain size (M_z, phi), porosity (η, %), bulk density (ρ, g cm^{-3}), and attenuation (k, dB m^{-1} kHz^{-1}).

Sediment Type	Regression	No of points	r^2
Siliciclastic	$V_pR = 1.603 - 0.0156\eta + 0.0001\eta^2$	3905	0.95
Calcareous	$V_pR = 1.760 - 0.0206\eta + 0.0001\eta^2$	609	0.91
All Sediments	$V_pR = 1.606 - 0.0158\eta + 0.0001\eta^2$	4514	0.95
Siliciclastic	$V_pR = 1.585 - 0.8991\rho + 0.3352\rho^2$	3905	0.94
Calcareous	$V_pR = 1.878 - 1.2289\rho + 0.4232\rho^2$	609	0.90
All Sediments	$V_pR = 1.649 - 0.9807\rho + 0.3595\rho^2$	4514	0.93
Siliciclastic	$V_pR = 1.184 - 0.0288M_z + 0.0008M_z^2$	2392	0.82
Calcareous	$V_pR = 1.161 - 0.0308M_z + 0.0013M_z^2$	371	0.82
All Sediments	$V_pR = 1.184 - 0.0307M_z + 0.0010M_z^2$	2763	0.82
All Sediments	$k = 0.74 - 0.07M_z - 0.02\,M_z^2$	2653	0.10
All Sediments	$k = -\,1.121 + 0.066\eta - 0.0006\,\eta^2$	4391	0.19

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